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13. ABSTRACT (Maximum 200 Words)

This is the final technical report for the Berkeley JSEP Program. As of July 31, 1998, all of the work units in the program were terminated except for one - "Quantum Computation: Exploring a Novel Computational Paradigm" which is led by Prof. Umesh Vazirani.

In this final report, a summary description of each of those work units that terminated in 1998 is given, as well as an up to date report of the work done in the Quantum Computing work unit.

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Director's Overview

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In this final report, a summary description of each of those work units that terminated in 1998 is given, as well as an up to date report of the work done in the Quantum Computing work unit.

Laser Processing for Liftoff of GaN-Thin Films from Sapphire Substrates

V. Cheung and Eicke R. Weber with William S. Wong

Research objectives are: 1) development of large-area liftoff by laser processing for sapphire substrates, 2) development of a metallurgical bonding process to bond GaN to Si or GaAs, and 3) integration of the bonding and liftoff processes for separation and transfer of GaN thin films from sapphire substrates onto more common semiconductor substrates such as Si or GaAs.

3. Status of Effort

Gallium nitride (GaN) thin films on sapphire substrates have been successfully separated and transferred onto Si substrates by pulsed UV-laser processing. A single 600 mJ/cm², 38 ns KrF excimer laser pulse was directed through the transparent substrate to induce a rapid thermal decomposition of the GaN at the GaN/sapphire interface. The decomposition yields metallic Ga and N₂ gas that allows separation of the GaN film from the substrate by warming the laser processed sample above melting point of Ga ($T_m=30^\circ\text{C}$) on a hot-plate.

4. Accomplishments/New Findings

GaN thin films on sapphire substrates were also successfully bonded onto Si and GaAs using an In/Pd metallic bi-layer. A strong adherent bond resulted after annealing the composite structure at 200°C. Liftoff and transfer of the GaN from sapphire onto Si or GaAs was then accomplished using a rastered laser-liftoff process to separate GaN. The laser rastering technique has yield liftoff of > 10 cm² GaN films. Characterization of the separated and transferred GaN thin films by x-ray diffraction (Figure 1), scanning electron microscopy, and atomic force microscopy also show that structural properties do not degrade after the bonding and liftoff process.

Three-micron-thick free-standing GaN membranes were also fabricated using the laser liftoff technique. Surface roughness of the exposed interfacial layer was measured to be ~24 nm (rms) by atomic force microscopy. Photoluminescence and x-ray diffraction measurements of the GaN showed no optical nor structural degradation of the films after liftoff from the sapphire. Based on a 10 meV red-shift of the donor-bound exciton peak, an estimated biaxial compressive stress of ~0.4 GPa in the GaN film was relieved by separation from the sapphire growth substrate (Figure 2).

5. Personnel Supported

William S. Wong

6. Publications and Conference Presentations

Publications

1. W.S. Wong, J. Krüger, Y. Cho, B.P. Linder, E.R. Weber, N.W. Cheung, and T. Sands, "Selective UV-laser processing for lift-off of GaN thin films from sapphire substrates", Proceedings of the Symposium on LED for Optoelectronic Applications and the 28th State of the Art Programs on Compound Semiconductors 98-2, 377 (1998).
2. W.S. Wong, T. Sands, and N.W. Cheung, "Damage-free separation of GaN thin films from sapphire substrates", Appl. Phys. Lett. 72, 599 (1998).
3. S. Sudhir, H. Fujii, W. S. Wong, C. Kisielowski, N. Newman, C. Dieker, Z. Liliental-Weber, M. D. Rubin, and E. R. Weber "Control of the structure and surface morphology of gallium nitride and aluminum nitride thin films by nitrogen background pressure in pulsed laser deposition", J. Electronic Materials 27, No. 4, 1998.

Conference Presentations

1. "Bandgap Selective Processing for Lift-off of GaN Thin Films from Sapphire Substrates", W.S. Wong, N.W. Cheung, and T. Sands, presented by W.S. Wong at the Workshop on Compound Semiconductor Materials and Devices (WOCSEMMAD), Monterey, CA, February 1998.
2. "Pulsed-Excimer Laser Processing for the Separation of GaN Thin Films from Sapphire-Substrates", W.S. Wong, J. Krueger, Y. Cho, B.P. Linder, E.R. Weber, N.W. Cheung, and T. Sands, presented by W.S. Wong at the 193rd Meeting of the Electrochemical Society, San Diego, CA May 1998.
3. "Selective UV-Laser Processing for Liftoff of GaN Thin Films from Sapphire Substrates", W.S. Wong, B.P. Linder, J. Krueger, Y. Cho, E.R. Weber, N.W. Cheung, and T. Sands presented at the Semi-Insulating Materials Conference X (SIM-X) Berkeley, CA, June 1998.
4. "Separation of GaN Thin Films from Sapphire Substrates Using Pulsed Laser Processing" W.S. Wong, T. Sands, and N.W. Cheung, presented by W.S. Wong at the 1998 Materials Research Society Spring Meeting, San Francisco, CA, April 1998.
5. "Selective Laser Processing for Lift-Off of GaN Thin Films from Sapphire Substrates", W.S. Wong, J. Krueger, Y. Cho, E.R. Weber, T. Sands, and N.W. Cheung, presented by W.S. Wong at the 40th Electronic Materials Conference, June 1998.
6. "Excimer Laser Liftoff of Epitaxial Piezoelectric Thin Films," T. Sands, L. Tsakalakos, W.S. Wong and G.M. Dougherty, presented by T. Sands at the DARPA Piezocrystals Teaming Workshop, Fairfax, VA, July 1998.

7. Interactions/Transitions

Collaboration has begun with Hewlett-Packard Company, Optoelectronics Division, San Jose, CA. The collaboration will focus on large-area laser liftoff of GaN thin films grown on sapphire substrate and developing the laser process to liftoff GaN based blue light-emitting device structures.

8. New Discoveries, Inventions, or Patent Disclosures

Invented and currently developing a laser liftoff process for separation of GaN thin films from sapphire substrates. The patent application, "Controlled Separation of Thin Films from Transparent Substrates by Selective Optical Processing" by N.W. Cheung, T. Sands, and W.S. Wong is currently being filed by the University of California.

9. Honors/Awards

Best Poster Presentation, Materials Research Society Spring 1998 Meeting, "Separation of GaN Thin Films from Sapphire Substrates Using Pulsed Laser Processing" W.S. Wong, T. Sands, and N.W. Cheung, presented by W.S. Wong, San Francisco, CA, April 1998.

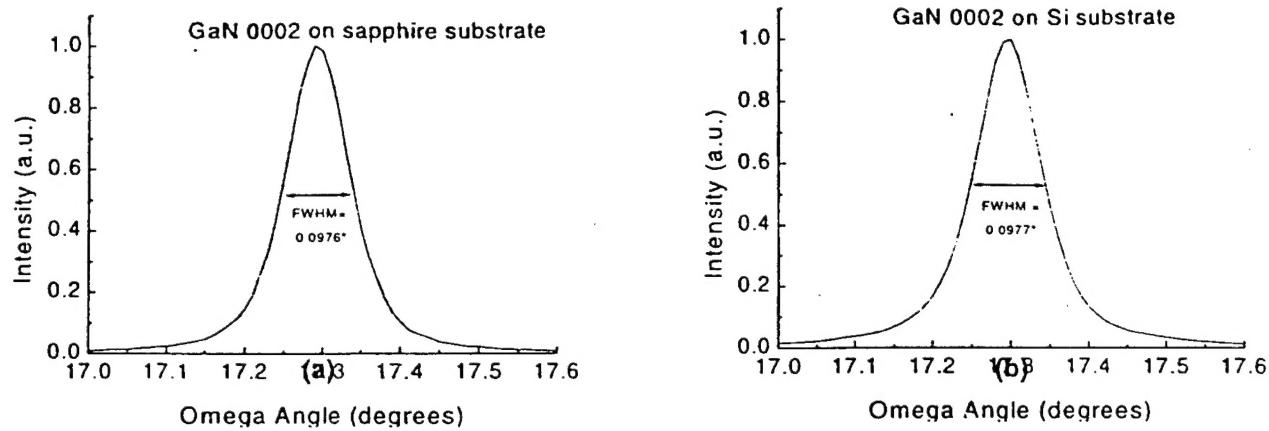


Figure 1: Comparison of GaN film quality by x-ray rocking curve of the 0002 GaN reflection for: (a) GaN on sapphire, and (b) after transfer from sapphire to a Si substrate. The FWHM of the 0002 GaN reflection remains unchanged after lift-off indicating that the film was separated and transferred without appreciable thermal or mechanical damage. A laser fluence of 600 mJ/cm^2 was used.

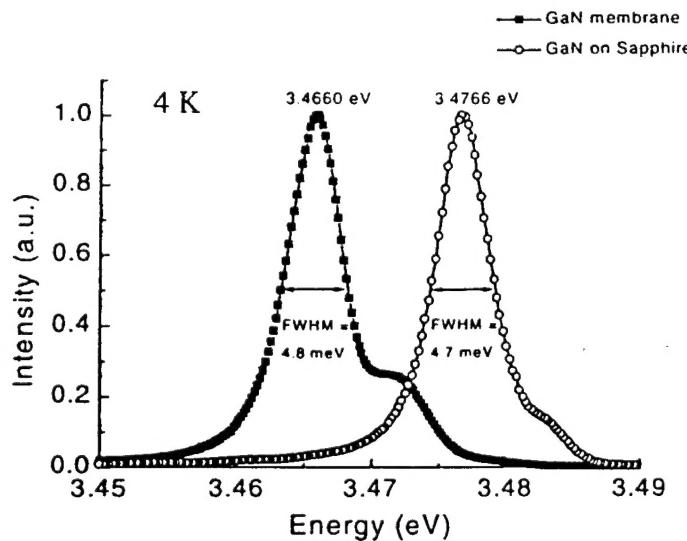


Figure 2: Low-temperature (4 K) PL spectra for GaN/sapphire and GaN membranes. The measured FWHM of the DX peaks after separation did not show appreciable broadening, indicating no detectable optical degradation of the GaN films. The measured red-shift of $\sim 10 \text{ meV}$ for the GaN membrane corresponds to a biaxial compressive stress relief of approximately 0.4 GPa after separation of the GaN from sapphire.

Cellular Neural Network Models and Nonlinear Dynamics of Quantum-Coupled Nanoelectronics.

Professor Chua

2. Objectives:

Cellular Neural Network technology is close to real-life applications. To make high-tech useful applications theoretical work, application studies, and implementation efforts are needed. The most critical part is the implementation. Two important steps were targeted and achieved (16x16 CNNUM and ARAM) in this field. Beyond the present importance, these results help solve the future problems of the quantum-coupled CNN devices also.

3. Status of Effort:

The work is continued. There are current efforts using and testing the ARAM and the 16x16 CNNUM chips in numerous applications. The theoretical works are continued also.

4. Accomplishments/New Findings:

The research was conducted in three fields:

- *Theory:* New results were achieved in CNN stability [1,8], in the mathematical morphology [7], and in cellular automata [9].
- *Application:* CNN applications for object segmentation and recognition [3], and halftoning were developed [5].
- *Implementation:* The first analog input-analog output CNN chip [4] and an analog RAM (ARAM) were developed partially supported by this grant [6]. Moreover, new synaptic operators were studied [2].

5. Personnel Supported:

The following persons were partially supported: Jose Cruz, Ricardo Carmona, Kenneth Crounse, Istvan Szatmari, Akos Zarandy

6. Publications:

1. N. Takahashi, L.O. Chua, "On the Complete Stability of Nonsymmetric Cellular Neural Networks", IEEE Trans. on Circuits and Systems I: Fundamental Theory and Applications, (CAS-I), Vol. 45. No.7. pp: 754-758, 1998
2. R. Dogaru, K.R. Crounse, L.O. Chua, "An Extended Class of Synaptic Operators with Application for Efficient VLSI Implementation of Cellular Neural Networks", IEEE Trans. on Circuits and Systems I: Fundamental Theory and Applications, (CAS-I), Vol. 45. No.7. pp: 745-753, 1998
3. Schultz, Cs. Rekeczky, I. Szatmári, T. Roska and L. O. Chua, "Spatio-temporal CNN Algorithm for Object Segmentation and Object Recognition", Proceedings of IEEE Int. Workshop on Cellular Neural Networks and Their Applications, (CNNA'98), pp. 347-352, London, 1998
4. J.M. Cruz, L.O. Chua, "A 16x16 Cellular Neural Network Universal Chip: The first Complete Single-Chip Dynamic Computer Array with Distributed Memory and with Grey-Scale Input-Output", Analog Integrated Circuits and Signal Processing, (Analog Integrated CASP), Vol. 15. No.3. pp:227-238, 1998
5. K.R. Crounse, R.Tamas, L.O. Chua, "Some Methods for Practical Halftoning on the CNN Universal Machine", Proceedings of IEEE Int. Workshop on Cellular Neural Networks and Their Applications, (CNNA'98), pp. 337-342, London, 1998

6. R. Carmona, S. Espejo, R. Dominguez-Castro, A. Rodriguez-Vazquez, T. Roska, T. Kozek, L.O. Chua, "A 0.5μm CMOS CNN Analog Random Access Memory Chip for Massive Image Processing", Proceedings of IEEE Int. Workshop on Cellular Neural Networks and Their Applications, (CNNA'98), pp. 271-276, London, 1998
7. Á. Zarándy, A. Stoffels, T. Roska and L.O. Chua, "Implementation of Binary and Gray-Scale Mathematical Morphology on the CNN Universal Machine", IEEE Trans. on Circuits and Systems I: Fundamental Theory and Applications, (CAS-I), Vol. 45. No.2. pp: 163-168, 1998.
8. N. Takahashi, L.O. Chua, "A New Sufficient Condition for Nonsymmetric CNN's to Have a Stable Equilibrium Point", IEEE Trans. on Circuits and Systems I: Fundamental Theory and Applications, (CAS-I), Vol. 44. No.11. pp: 1092-1095, 1997
9. K.R. Crouse, E.L. Fung, L.O. Chua, "Efficient Implementation of Neighborhood Logic for Cellular Automata via Cellular Neural Networks Universal Machine", IEEE Trans. on Circuits and Systems I: Fundamental Theory and Applications, (CAS-I), Vol. 44. No.4. pp: 355-361, 1997
10. K.R. Crouse, "Image Processing Techniques for Cellular Neural Network Hardware" Dissertation, University of California Berkeley, 1997

7. Interactions/Transactions:

We are presently cooperating with Lockheed Martins Corporation to use the CNN Universal chip and ARAM developed under partial JSEP support for designing smart night vision systems via CNN real time image fusion techniques.

8. New Discoveries, Inventions, or Patent Disclosures:

None

9. Honors/Awards:

None

Single Mode Vertical Cavity Surface-Emitting Lasers (VCSELs)

C. Chang-Hasnain

k:

two major portions of this work aimed towards the goal of understanding the device physics of single-mode VCSELs. In the first part, we focused on the study of the spatial profile of gain and reflectivity in oxide-confined (OC) VCSELs. The OC VCSELs have been widely used in many research topics. However, due to the high index contrast, the laser aperture is required to be smaller than 3-4 micron in order to sustain single mode operation. In this work, the modal behavior of the oxide-confined lasers is studied using a two dimensional beam propagation method and multimode rate equations. We show that even a very thin oxide aperture can provide strong index guiding effect, driving the laser into multimode emission. We also show that by engineering the gain profile or the mirror reflectivity profile, a single fundamental mode emission can be obtained even for relatively large aperture VCSELs.

The second portion of the work included the calculation of diffraction loss in a variety of distributed Bragg reflectors (DBR). This problem had been examined before. However, its dependence on wavelength or DBR thickness variation were never examined. In this work, we calculate the diffraction loss by first Fourier transform a single mode beam into a sum of plane waves with a spectrum of k vectors, calculating the reflectivity for each plane wave component, and then perform inverse Fourier transform to attain the effective reflectivity. We show that for DBRs made with materials with a small index difference, the diffraction loss increases rapidly as the DBR thickness deviates away from the design of quarter-wave layers, and similarly, as the wavelength of interest deviates from the optimum wavelength.

Publications/Presentations:

1. "Effect of Spatial Profile of Gain and Reflectivity in Oxide-Confined VCSELs", Y. A. Wu, W. Yuen, and C. J. Chang-Hasnain, submitted to *Applied Physics Letters*. April 1998.

Ultrafast High Field Response in Semiconductors

Professor Jeffrey Bokor

2. Objectives:

The primary goal of this research is to develop a detailed fundamental understanding of the transient response of charge carriers subjected to strong electric fields in semiconductors.

3. Status of Effort:

The work on ultrafast time-resolved photoemission spectroscopy for the study of ultrafast carrier dynamics on Si (100) surfaces was completed. It has been documented in the Ph.D. thesis of S. Jeong, and a final publication is in press. The work on the development and use of high intensity THz pulses for the study of hot electron dynamics in GaAs and Si has also completed. It has been documented in the Ph.D. thesis of E. Budiarto and has been published.

This year, a new effort was begun on the study of ultrasonic resonances in multilayer thin film structures for characterization of their properties. These resonances are launched and detected using femtosecond visible laser pulses.

4. Accomplishments/New Findings:

Periodic multilayer structures with alternating films of Si and Mo are useful for reflection coatings for soft X-ray wavelengths. In particular, these coatings are being used in the development of EUV lithography which uses 13 nm radiation. We have found that a Mo/Si multilayer stack that gives high normal incidence reflectivity for 13 nm radiation is also an ultrasonic resonator at about 1 THz. The resonance is detected as an oscillating change in visible reflectivity following excitation by a 100 fsec laser pulse. We are investigating the nature of the oscillation as well as the detailed dynamics of its excitation by visible light. This effect appears to be useful as a low cost, non-destructive characterization tool. We've shown that the resonant frequency is directly proportional to the multilayer period, which is a critical parameter for lithography and other applications to soft X-ray optics.

5. Personnel Supported:

Faculty: Prof. Jeffrey Bokor

Graduate Students: Edward Budiarto, Seongtae Jeong, Nen-Wen Pu

6. Publications:

1. "Picosecond ultrasonic study of Mo/Si multilayer structures using a new alternating pumps technique," Nen-Wen Pu, Seongtae Jeong, Ri-An Zhao, and Jeffrey Bokor, submitted to Appl. Phys. Lett.
2. "Near-field propagation of terahertz pulses from a large-aperture antenna," Edward Budiarto, Nen-Wen Pu, Seongtae Jeong, and Jeffrey Bokor, Opt. Lett. 23, 213 (1998)
3. "High intensity terahertz pulses and their applications," Edward Budiarto, Ph.D. dissertation, EECS Department, University of California, Berkeley.
4. "Study of ultrafast hot-electron dynamics in silicon using time-resolved photoemission," Seongtae Jeong, Ph.D. dissertation, Physics Department, University of California, Berkeley.

7. Interactions/Transactions:

We have had extensive discussions with Jim Folta and Steve Vernon at Lawrence Livermore National Laboratories on the suitability of our picosecond ultrasonics technique as a diagnostic tool for multilayer coatings. They have supplied us with several samples and have been quite excited by our results.

8. New Discoveries, Inventions, or Patent Disclosures:

None

9. Honors/Awards:

None

Progress Report on JSEP Grant.

Quantum computation

Quantum computation is a revolutionary idea that has the potential to shape computation as it moves into the nano-scale. There have been a number of proposals for experimental realizations of quantum computation in the laboratory. The most successful of these to date is based on Nuclear Magnetic Resonance — experiments with four qubit quantum circuits have already been carried out, and six qubit experiments are already under way. One major problem that had to be overcome was the difficulty with initializing the quantum bits to a known initial state (say the all 0 state). This problem is hard because the NMR technology works with a bulk sample, rather than individual molecules. Indeed, the scheme for initialization that is currently used in experiments does not scale — the output signal decreases exponentially in the number of quantum bits in the circuit. The exponential advantage conferred by quantum computation is thus lost, since it is not possible to detect the output of the quantum circuits with more than twenty quantum bits. In [6], we gave a new scheme for initializing the quantum bits in an NMR quantum computer which scales. The scheme is optimal — it runs in nearly linear time, and yields the optimal number of clean qubits. The strength of the output signal is independent of the number of quantum bits.

Another important thread in research on quantum computation has been to explore the limitations of quantum algorithms. This is particularly important, since there are results such as Grover's search algorithm, which demonstrate how the power of quantum computation can be used to solve seemingly impossible problems. A fundamental question that had been open for some time was the following: given n bits b_1, \dots, b_n , how many samples are necessary to approximate their arithmetic mean to within ϵ ? Using classical sampling, it is well known that $\Theta(1/\epsilon^2)$ is a tight bound. However, an algorithm based on Grover's search algorithm provides an $O(1/\epsilon)$ quantum algorithm for solving this problem. On the other hand, the only lower bound for quantum algorithms was $\Omega(1/\sqrt{\epsilon})$, using BBBV's hybrid argument technique. In [5], a tight $\Omega(1/\epsilon)$ lower bound on this problem was proven. The main ingredient in the proof is a polynomial degree lower bound for real multilinear polynomials that "approximate" symmetric *partial* boolean functions. The paper also gives a new upper bound for the problem of computing an ϵ -approximate median, as well as a tight matching lower bound.

Quantum communication

Quantum communication is another exciting area where a combination of the cryptographic and information capacities of quantum channels, together with recent breakthroughs in technology are creating revolutionary opportunities. Indeed, there are already several successful experimental setups (at Los Alamos, IBM, CERN, etc) for quantum cryptography, that can transmit and decode single quantum bit photon pulses over distances of tens of kilometers.

Despite the exponential advantage of quantum bits (over classical bits) in the

context of computation, a fundamental theorem due to Holevo appears to rule out any such advantage in the context of communication. Holevo's theorem says that n quantum bits cannot be used to communicate any more than n classical bits. Nonetheless, in [2], we showed that there are certain kinds of communication tasks where quantum bits do provide exponential savings over classical communication. One example of such a task is dealing cards over the telephone: Alice has a cardinality \sqrt{n} subset of $\{1, \dots, n\}$, and Bob wishes to pick a uniformly random cardinality \sqrt{n} subset disjoint from Alice's subset. Classically, this task requires Alice to send $\Omega(\sqrt{n})$ bits to Bob. However, we showed that there is a quantum protocol that requires Alice to send only $O(\log n)$ quantum bits to Bob.

Another way of getting around Holevo's theorem — random access codes — was proposed in [1]. The idea was that since measurements do not commute in general, it is possible that exponential compression could be achieved if the recipient was interested in reading only one bit of an n bit message (i.e. encoding these using only $\log n$ quantum bits). If such random access codes were possible, then we could create a disposable quantum telephone directory, by encoding the contents of the entire directory in a few tens of quantum bits, such that the user could read off any (single) phone number of his choice. In [1, 4] it was shown that no more than a constant factor of compression is possible. These results provide a strengthening of Holevo's theorem.

[4] provides another direction in which Holevo's theorem can be strengthened, by providing tight bounds on the probability of correct decoding when quantum bits are used to transmit classical information over a quantum channel. These new results also yield tight lower bounds on the computational power of space-restricted devices — general quantum finite automata — for certain computational tasks.

Quantum Cryptography

Unconditionally secure bit commitment and coin flipping are known to be impossible in the classical world. Bit commitment is known to be impossible also in the quantum world. In [3] we introduce a related new primitive - *quantum bit escrow*. In this primitive Alice commits to a bit b to Bob. The commitment is *binding* in the sense that if Alice is asked to reveal the bit, Alice can not bias her commitment without having a good probability of being detected cheating. The commitment is *sealing* in the sense that if Bob learns information about the encoded bit, then if later on he is asked to prove he was playing honestly, he is detected cheating with a good probability. Rigorously proving the correctness of quantum cryptographic protocols has proved to be a difficult task. We develop techniques to prove quantitative statements about the binding and sealing properties of the quantum bit escrow protocol.

A related primitive we construct is a quantum biased coin flipping protocol where no player can control the game, i.e., even an all-powerful cheating player must lose with some constant probability, which stands in sharp contrast to the classical world where such protocols are impossible.

References

- [1] A. Ambainis, A. Nayak, A. Ta-Shma and U. Vazirani. Dense quantum coding and a lower bound for 1-way quantum automata. *Proceedings of the Thirty-First Annual ACM Symposium on the Theory of Computing*, 1999, pp. 376–383.
- [2] A. Ambainis, L. Schulman, A. Ta-Shma and U. Vazirani. The Quantum Communication Complexity of Sampling. *Proceedings of the 39th Symposium on the Foundations of Computer Science*, 1998.
- [3] D. Aharonov, A. Ta-Shma, U. Vazirani, A. Yao. Quantum Bit Escrow. *Proceedings of the Thirty-Second Annual ACM Symposium on the Theory of Computing*, 2000.
- [4] A. Nayak. Optimal lower bounds for quantum automata and random access codes. *Proceedings of the 40th Symposium on Foundations of Computer Science*, 1999.
- [5] A. Nayak and F. Wu. The quantum query complexity of approximating the median and related statistics. *Proceedings of the Thirty-First Annual ACM Symposium on the Theory of Computing*, 1999, pp. 384–393.
- [6] L. Schulman and U. Vazirani. Molecular Scale Heat Engines and Scalable Quantum Computation. *Proceedings of the 30th Annual Symposium on the Theory of Computing*, 1999.

of Professional Personnel

Students:

Wilsin Gosti

Connie Chang-Hasnain
Chenming Hu
Tsu Jae King
Christos Papadimitriou
Alberto Sangiovanni-Vincentelli
Umesh Vazirani
Eicke Weber

Post Doctorates:

Ricardo Carmona
Giorgio Giarettta
Tabor Cossack
Su-In Wu

Advanced Degrees Awarded:

| | | | |
|--------------------|-------|----------|--|
| Edward Budiarso | Ph.D. | Dec 1997 | High Intensity Terahertz Pulses and Their Applications |
| Christopher Gworek | M.S. | Dec 1999 | The Schottky Barrier Height of Noble Metal Schottky Contacts to n-GAs under Hydrostatic Pressure |
| Seongtae Jeong | Ph.D. | Dec 1997 | Study of ultrafast hot electron dynamics in silicon using time-resolved photoemission |
| Wen-Chin Lee | M.S. | Dec 1997 | Impact on MOS Gate Doping Technologies on Device Performance and Reliability |
| Wen-Chin Lee | Ph.D. | Dec 1999 | Poly-Si Ge Gate Technology and Direct-Tunneling Oxide of Deep Submicron CMOS Application |
| Gabriel Li | Ph.D. | 1998 | Wavelength Selective Detectors for Fibre-Optic Communications |
| Melissa Li | Ph.D. | 1998 | Micro-Mechanical Tunable Vertical-Cavity Surface-Emitting Lasers |
| Sui Lim | Ph.D. | 1998 | VCSEL with an Intracavity Quantum-Well Absorber: Design and Applications |

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| Ashwin Nayak | Ph.D. | Dec 1999 | Lower Bounds for Quantum Computation and Communication |
| L. Schloss | M.S. | Dec 1996 | GaN Semiconductor Device Issues |
| G.S. Sudhir | Ph.D. | May 1999 | Effect of Strain on GaN and AlInAsN Growth and Doping |
| Stephen Tang | M.S. | May 1997 | Subthreshold Current Modeling for Short-Channel Mosfets |
| Adrian Wrixon | M.S. | Dec 1998 | New Directions in Static and Dynamic Variable Ordering of Binary Decision Diagrams |
| William S. Wong | Ph.D. | Dec 1999 | Integration of GaN Thin Films with Dissimilar Substrate Materials by Wafer Bonding and Laser Lift-off |
| Bin Yu | M.S. | May 1996 | Lateral Channel-Engineering & Short-Channel Effect in Deep-Submicrometer Mosfet's |